A 180-year Climatology of Severe Weather Environments in the United States

HOPE SKYPEK*

National Weather Center Research Experiences for Undergraduates Program
Norman, Oklahoma,
The University of Georgia
Athens, Georgia

HAROLD BROOKS

NOAA Severe Storms Laboratory
Norman, OK

KIMBERLY HOOGEWIND

Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma
and NOAA Severe Storms Laboratory
Norman, OK

ABSTRACT

This study evaluates a 180-year climatology for the period 1836–2015 of severe weather environments in the United States using 20th Century Reanalysis version 3. Various composite thresholds are utilized to establish severe weather environments and the number of days of these severe weather environments (NDSEV) calculated for each year. Regional comparisons demonstrate trends of frequency of severe storm environments for various geographic regions of the U.S. Annual cycles are analyzed to explore seasonality of severe weather. Compared to the mid 19th century, NDSEV in the Southeast has increased by 15.7 days and decreased in the Northern Plains by 15.5 days. The beginning of severe weather season has moved over a month earlier in the year. Additionally, potential inconsistencies are in the reanalysis are subjectively identified, specifically in evaluated magnitudes of severe storm parameters.

1. Introduction

From the 21st century alone, it is evident that atmospheric conditions spawning severe thunderstorms and tornadoes can be disastrous. Roughly five notable events in the past twenty years have been prolonged for 1–2 weeks and spanned across at least half of the United States according to Storm Prediction Center records (2003, 2005, 2011, 2013, 2019). For example, the 2003 extended outbreak of tornadoes from May 3 to 11 produced at least 13 tornadoes each day for 9 consecutive days across 28 states. This resulted in 41 fatalities and almost one billion dollars of damage (Hamill et al. 2005). Due to the devastation resulting from periods like May 2003, analyzing the conditions of certain periods with anomalously above-climatology tornado frequency has been of great interest to researchers for years.

While we are able to study these more recent events due to upper air observations and radar imagery, analyzing severe weather events more than 60 to 70 years back is complicated. Adequate weather observation technology did not exist and the National Weather Service did not start collecting consistent data on tornadoes until the mid 20th-century. Relatively short climatologies dating back to the 1970s have been created and make suggestions about temporal and spatial trends of tornadic activity. Several studies have shown an increase in tornado frequency and environments favorable for tornadoes in the eastern United States and a decrease in the Great Plains (Gensini and Brooks 2018; Farney and Dixon 2015). Other studies have indicated an increase in temporal variability of tornadoes and tornado favorable environments, meaning that there may be more ”big” tornado days and more tornadoes overall in the future, though the number of tornado days remains relatively stable (Brooks et al. 2014; Tippett 2014). The biggest problem with studying severe weather climatology is that well-documented atmospheric variables are limited, so a longer dataset is necessary for

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* *Corresponding author address:* Hope Skypek, University of Georgia, Athens, Georgia
E-mail: hopeskypek98@gmail.com

sufficient sample sizes to gain a better understanding or come to conclusions about long-term trends.

Due to the lack of a reliable, long-term record of severe weather observations, historical reanalysis data has been widely used to analyze climatological distributions of environments favorable for severe storms. Reanalysis essentially uses past observations and modern weather forecast models to create a historical reconstruction of the atmosphere. These datasets provide researchers with the opportunity to gain understanding of historical weather, but most past projects have emphasized that a longer and more reliable dataset is still necessary to come to conclusions from a climatological perspective (Gensini and Ashley 2011; Brooks et al. 2003). Reanalyses have been beneficial tools overall, but have had accuracy issues with thermodynamic data (Gensini et al. 2014). However, version 3 of the 20th Century Reanalysis (20CRv3) recently became available with upgraded data assimilation methods and significant bias reductions. This model is able to provide insight on nearly 200 years of atmospheric conditions from surface pressure data (Slivinski et al. 2019). 20CRv3 is a unique reanalysis dataset with exceptional temporal and spatial coverage, allowing for the opportunity to analyze severe storm environments over a longer period of time.

This study will evaluate how 20CRv3 encapsulates severe storm environments dating back to the 19th century. If prominent events are displayed relatively well compared to historical records, we may have a promising future of examining environments conducive to storms throughout history with 20CR. Secondly, this study creates a climatology of severe weather parameters from 1836 to 2015 using an ingredients-based approach. By examining environments known to promote severe weather with historical reanalysis data, the biases and variations of storm-reporting can be avoided (Gensini and Ashley 2011; Tippett 2014). Understanding the long-term trends of severe weather events may enable forecasters to make predictions at longer lead times, potentially protecting life and property.

2. Data and methods

This study exploits 20CRv3 data obtained from the National Oceanic and Atmospheric Administration (NOAA) Physical Science Laboratory (PSL). 20CRv3 assimilates surface pressure observations into an 80 member ensemble of model forecasts to provide 3D reconstructions of the atmosphere, using sea surface temperatures and sea ice concentrations as boundary conditions. The 2017 version of the National Center for Environmental Prediction (NCEP) Global Forecast System (GFS) is used as the model. Spatial resolution consists of about 0.5° horizontal resolution and 64 vertical hybrid sigma-pressure levels. Post processed data were obtained from PSL at 1° horizontal grid spacing (Slivinski et al. 2019). The data provide an estimate of the state of the atmosphere every 3 hours from 1836 to 2015 and yields parameters at greater spatiotemporal resolution than sounding data.

Severe storm environments are often characterized by deep wind shear and convective available potential energy (CAPE). To employ an ingredients-based approach to evaluate severe storm environments, 3D variables of pressure, temperature, moisture, and winds were used to derive various thermodynamic and wind shear parameters for the period 1836–2015. Surface-based CAPE (sbCAPE), 0–6 km bulk wind shear (S06), and storm-relative helicity (SRH; 0–1 km and 0–3 km) were evaluated to observe variables supportive of severe storms, rather than analyzing storms themselves. Two composite parameters, Significant Tornado Parameter (STP; Thompson et al. 2003) and the product of CAPE and S06 (CAPES06) (Brooks et al. 2003) were calculated using their necessary constituents. Both are commonly used indices to indicate statistical tornadic potential and are calculated by

$$STP = \left(\frac{sbCAPE}{1500}\right) \times \left(\frac{2000 - sbLCL}{1000}\right) \times \left(\frac{SRH1}{150}\right) \times \left(\frac{6BWD}{20}\right) \times \left(\frac{200 + sbCIN}{150}\right)$$

and

$$CAPES06 = sbCAPE \times S06$$

respectively. 2 was applied only after initial criteria are satisfied: CAPE ≥ 100 J kg^{-1} and S06 ≥ 5 m s^{-1}.

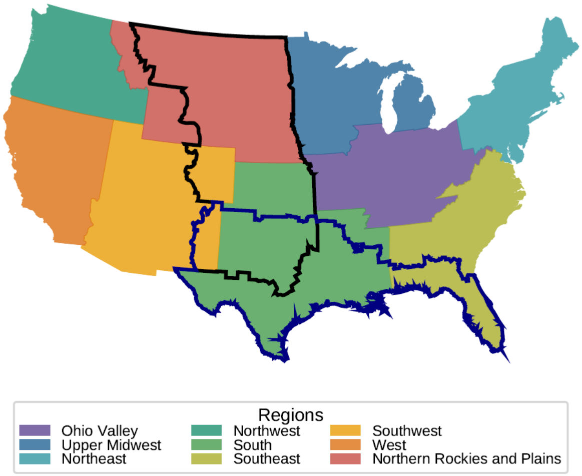

FIG. 1. Regional boundaries used for spatial analysis. Outlined in blue is the Southern Plains and Gulf Coast and outlined in black is the Great Plains.

Because we used mean values from the 20CRv3 ensemble, some assumptions were necessary. The first assumption was that its thermodynamic outputs are relatively accurate in comparison to other outputs and that ensemble data prevents straying far from the truth. It is well documented that thermodynamic variables produced by models rely on parameterizations and are influenced by the vertical resolution (Gensini et al. 2014). Therefore, integrated thermodynamic parameters, such as CAPE and CIN, are less reliable than wind variables. Larger confidence intervals for these variables may dampen their values (or composite parameters using CAPE in their calculations). These confidence intervals decrease chronologically, meaning that output from the earliest periods of the dataset produce values with the lowest confidence. We included these uncertainties and assumed that they were generally accurate.

The ingredients-based approach does not account for lifting mechanisms required for thunderstorm initiation, but analyzes the environments under which they are likely to occur given a source of lift. This often leads to an overestimation of quantities of severe storm days in historical reanalysis. Despite this, we assume that this approach is a feasible representation as shown in several studies (Gensini and Brooks 2018). We aim to examine the trends of severe storm ingredients to gain a sense of usefulness throughout the dataset.

Early output from 20CRv3 could initiate more confidence in the model by predicting specific severe storms in the same periods in which they actually occurred. This was first evaluated with the extended, high-impact storm outbreaks produced in May 1896. Parameters associated with convective storms from May 1896 were analyzed, focusing on STP, sbCAPE and 0–6 km bulk wind shear. When mapped, convective precipitation and STP daily maximum values adequately reconstructed the timing and location of many of the high-impact days based on historical records (Fig. 2). The identifications of these notable (high storm activity) periods from the climatology allowed us to continue to evaluate how well the reanalysis detected them.

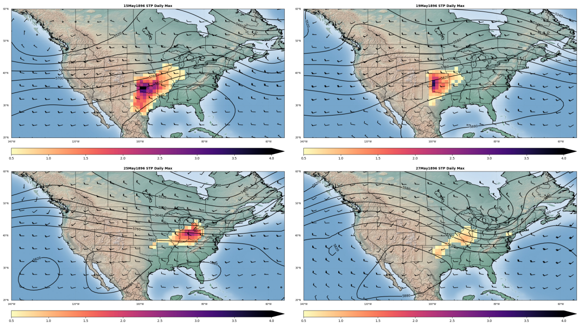

FIG. 2. Reconstruction of the daily maximum STP on several days of the May 1896 storm outbreak. Significant tornadoes were reported in a) Denton, TX and Durant, OK on May 15, b) Kansas and Nebraska on May 17, c) Illinois and Southeast Michigan on May 25, d) St. Louis, Missouri and Mexico, Missouri on May 27.

To evaluate overall trends and anomalous periods of severe storm environments, climatological analyses were performed with focus on (1) spatial frequency and variation; (2) the annual cycle; and (3) variation in magnitudes of severe storm parameters. Time plots of days per year reaching various thresholds were constructed (Craven and Brooks 2004). Days with STP ≥ 1 and CAPES06 $\geq$ 10,000 were created to look at the number of days with severe thunderstorm environments (NDSEV). Days with CAPES06 $\geq$ 20,000 were considered significant severe days (NDSEVsig). To assess severe weather environments by geographic region, spatial maps of 30 year averages and their anomalies from the entire period were constructed. Focusing on time plots by region and spatial maps of NDSEV, NDSEVsig, and STP and their components allowed us to qualitatively evaluate temporal and spatial trends.

Although this version of 20CR is shown to have vast improvements from previous versions through bias corrections, remaining wind and precipitation issues in early periods are still possible (Slivinski et al. 2019). This study assesses whether 20CRv3 output is reasonable to a degree, but the primary goal is to identify large-scale patterns and trends of severe weather environments. Future work has potential to verify these results and gain understanding of the mechanisms behind them.

3. Results

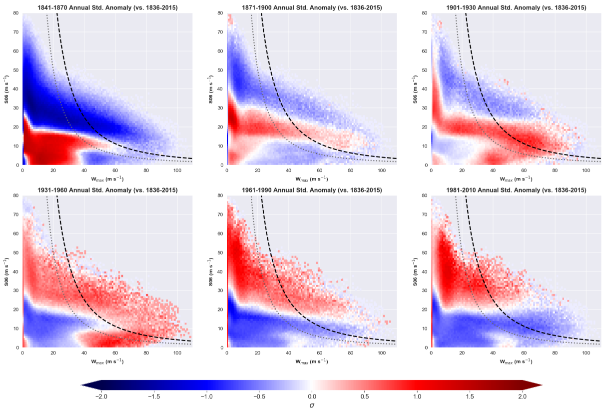

FIG. 3. 2D histogram (w_{max} vs. S06) of standardized anomaly of 30-year periods compared to the whole. The dotted line is the severe storm threshold, and the dotted line is the significant-severe storm threshold.

An analysis of the relationship between w_{max} ($w_{max} = \sqrt{2 \times CAPE}$) and S06 and how it has changed over time shows an increase and shear and decrease in w_{max} (or

CAPE) in severe and significant-severe environments. This signifies that of NDSEV, the proportion of environments with high deep-level shear and moderate w_{max} is increasing. Taszarek et al. (2017) found that high deep-level shear and moderate w_{max} creates an environment that gives the highest probability of tornado formation in Europe. Other parameters such as LCL and storm-relative helicity are relevant, and only accounting for these two variables is an oversimplification of reality. However, it appears that severe storm environments have become more favorable over time as represented by the reanalysis.

Spatial variability

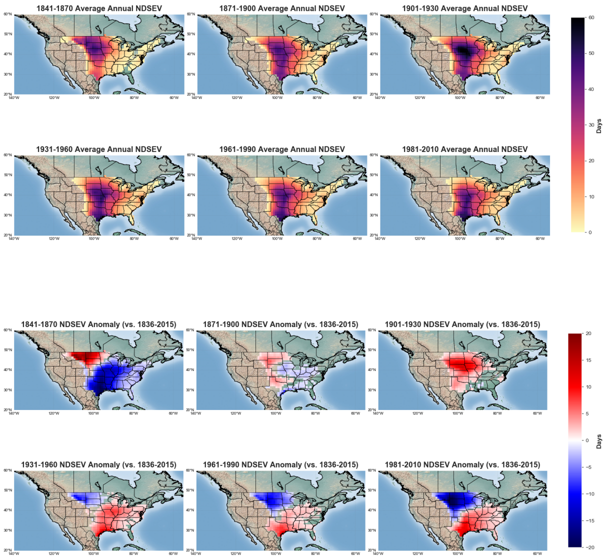

FIG. 4. NDSEV days (CAPES06≥10,000) for each averaged 30-year period (top) and their anomalies relative to the entire averaged 180-year period (bottom).

Spatial maps of anomalies of 30-year periods show consistent patterns of regional trends of NDSEV, specifically in two distinct regions (Fig. 4). Regional variability depicted is relatively similar to that of previous tornado and severe storm climatology research (Gensini and Brooks 2018; Farney and Dixon 2015). There consistently is a gradual increase in NDSEV in the eastern United States and a gradual decrease in the north and central U.S., suggesting a change in storm frequency favoring the southeast throughout the 180-year period. The spatial maps only show regions that had any NDSEV days on average, so negative anomalies do not mean that NDSEV did not occur. The Northern Plains are still a hot spot for severe weather as depicted in Fig.4, but potentially becoming less of one over time. The Southern Plains and Gulf Coast region encompass areas with the most significant changes between averages of the first 30-year period (1841–1870) and the most modern (1986–2015), increasing by approximately 15.7 days of a severe weather threshold being reached. A similar increase of 12.5 days occurred in the Ohio Valley, and such increases are consistent across the entire eastern U.S. Meanwhile, maximum decreases in NDSEV occurred in the Northern Plains, with a loss of approximately 15.5 days total.

The number of days in which significant CAPE values were reached (CAPE $\geq$ 1,000 J kg^{-1}) had very similar spatial trends to those of NDSEV days. Increases in the number of days of CAPE $\geq$ 1,000 J kg^{-1} occurred in the eastern U.S., while decreases occurred in the Northern Plains. This finding signifies that spatial variability of CAPE drove the corresponding increases and decreases of NDSEV days by region, whether this was a result of physical mechanisms or not. The changes in NDSEV and days with CAPE $\geq$ 1,000 J kg^{-1} were statistically significant with 95% confidence in both the Southern Plains and Gulf Coast region and the Northern Plains region. However, temporal components made these correlations less straightforward. The increase of NDSEV in the Southeast occurs most in the spring (March, April, and May) while the decrease in the Northern Plains primarily occurs in mid-to-late summer (July and August). Meanwhile, days of CAPE $\geq$ 1,000 J kg^{-1} showed minimal seasonal variability. This suggests that changes in CAPE may have driven spatial trends, while changes in S06 influenced the seasonality of these spatial trends.

Annual Cycle

As previously shown, the United States has experienced a slight increase in NDSEV overall, with the response being driven by mostly increases in springtime freqeuency. This is evident when examining the mean cumulative distribution function (CDF) of NDSEV, which quantifies the proportion of days accumulated by the corresponding day of the year (Fig. 5). The proportion of total annual NDSEV occurring earlier in the year is greater for each climatological period until August, where the two most recent periods are no longer higher than the previous four periods.

More significant changes appear to occur within seasonality, as each NDSEV index shows overall increases in the spring months (March, April, May) and decreases in the mid-to-late summer months (July, August, September) over the 180-year period. April and August had the most significant changes in severe days, with a moving average of April NDSEV surpassing that of August around 1960. Changes in seasonality appear to occur most drastically in the Southern Plains and Gulf Coast, though NDSEV increases in the spring and decreases in the late summer across the entire United States (Fig. 6). The idea that severe season is beginning and peaking earlier has been observed in prior research. These findings suggest that the

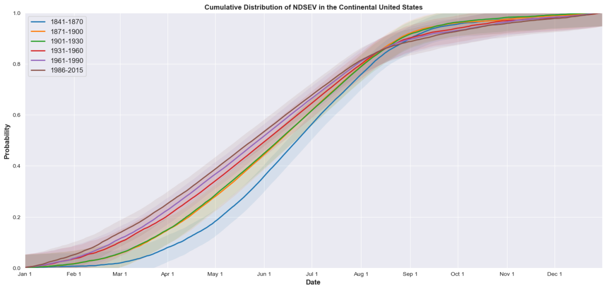

FIG. 5. Mean ECONUS (areas east of 105°W) cumulative distribution function of annual NDSEV for each averaged 30-year period with 95% confidence intervals shaded.

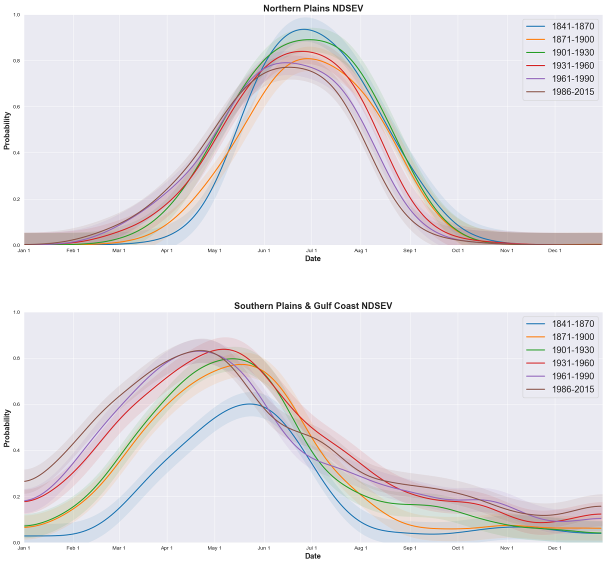

FIG. 6. Probability of NDSEV for (top) Northern Rockies and Plains and (bottom) Southern Plains and Gulf Coast by Julian date (smoothed with Gaussian filter, sigma = 15 days) for each averaged 30-year period. Smoothed 95% confidence intervals are shaded.

peak has not always occurred in the spring months (Long et al. 2018; Lu et al. 2015). This trend is consistent and fairly linear through the entire time period.

In addition to this shift of means, the spread and overall shape of the distributions of each period also change (Fig. 7). Each index is in agreement that the 5th percentile of NDSEV and NDSEVsig has shifted to earlier in the year. If we consider this to be the start of the severe weather season, these results indicate that the beginning of the season occurs earlier within the year at a rate of approximately 3.6 days per decade and 4.4 days per decade for NDSEV and NDSEVsig, respectively. This result came from the slope of a linear regression analysis of various percentiles of NDSEV and NDSEVsig (Fig. 7).

Each index also agrees on an increase of the length of severe weather season, although by different magnitudes (Table 1). The other extreme, the 95th percentile, even shows a statistically significant trend of the end of NDSEV and NDSEVsig occurring later in the year for both CAPES06 thresholds. In other words, the majority of NDSEV are occurring earlier on average, with the exception of days later in the year. A linear regression reveals an increase of the length of severe weather season of approximately 6 days per decade (considering the 95th percentile to be the end of the season). Likewise, the length of NDSEVsig season increases at a rate of approximately 7 days per decade. The change of each plotted percentile is statistically significant at 95% confidence, as tested by the Mann-Whitney U test.

Magnitude trends

Analyses of average magnitudes of CAPES06 over time reveal temporal inconsistencies in the data. There appears to be 3 evident time periods with different trends in these magnitudes with abrupt breakpoints occurring around 1875, 1945, and 1970. We speculate that changes this sharp likely are not physical and point to some issue with the observations assimilated into the reanalysis. We could not conclude whether or not the truthful general trend was similar to the magnitudes produced by the reanalysis and if any physical mechanisms may have been responsible. It is possible that the trends within certain time periods are relatively accurate, but require different thresholds due to distinct changes in observations.

Magnitudes of CAPE and S06 given NDSEV were evaluated separately. Mean CAPE magnitudes in severe environments remained relatively stable until 1960, and then experienced a steady decline. This could be a driver of the STP trends seen in Gensini and Brooks (2018) and Trapp and Hoogewind (2018). We can note this is at odds with projected increases in CAPE under anthropogenic climate change (e.g., Hoogewind et al. 2017). Mean S06 magnitudes were also questionable and showed abrupt breaks similar to CAPES06, indicating that the most inconsistencies may exist in the vertical wind fields of the dataset.

Further qualitative analysis of spatial trends of the constituents of CAPES06 revealed that annually, NDSEV in the Northern Plains region are strongly correlated with the highest average CAPE values in the U.S. This pattern is consistent throughout every time period and experience minimal change over time. The magnitudes of these CAPE values in the Northern Plains show gradual decreases over time, particularly after 1960. These results align with time plots of CAPE magnitudes as well as spatial trends of decreased storm environment frequency in the central U.S. On the other hand, it appears that NDSEV in the eastern U.S.and Gulf Coast are driven by the highest shear values. Interestingly, a widespread increase in mean shear values within these environments is depicted. These results are equally consistent in the more recent periods with higher confidence. However, the validity and

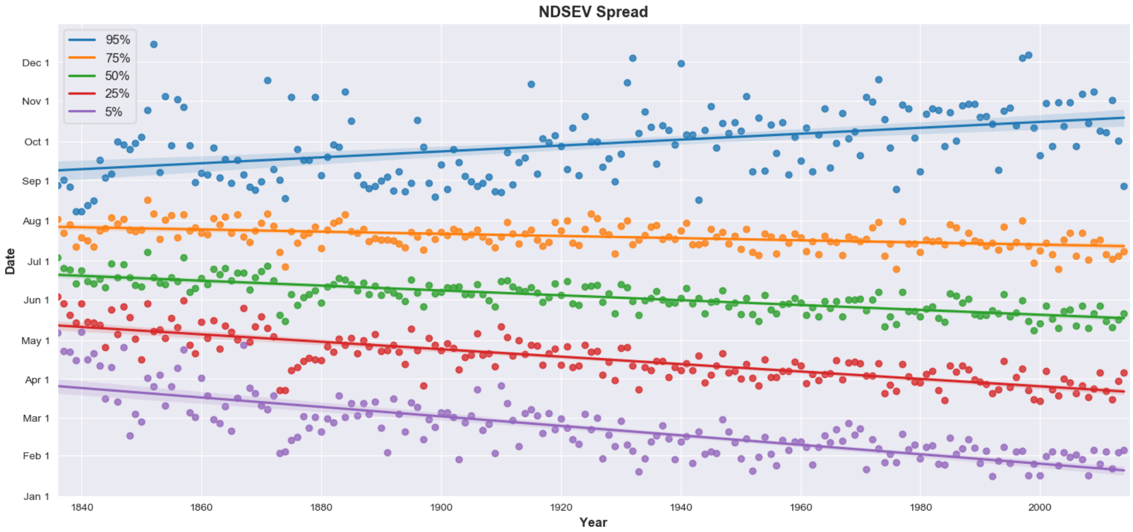

Fig. 7. Date of the 5th, 25th, 50th, 75th, and 95th percentiles of NDSEV (CAPES06$\geq$10,000) CDF by year with plotted linear regressions of each.

Table 1. Seasonal changes of the spread of NDSEV (in days) over the 180-year period.

Percentile	CAPES06$\geq$10,000	CAPES06$\geq$20,000	STP$\geq$1
0.05	-79.8	-65.6	-63.3
0.25	-65.3	-51.4	-47.3
0.50	-46.4	-33.7	-41.4
0.75	-17.6	-15.0	-36.7
0.95	+33.7	+40.9	-30.9

physical mechanisms behind these constituent patterns are potential areas for future research.

4. Discussion

Assessing severe storm climatology comes with many limitations, leading researchers to employ various approaches for decades. This study uses an ingredients-based approach of severe storm thresholds to quantify NDSEV and NDSEVsig, a method that has been widely used in similar research. A noted limitation of the reanalysis approach is that it does not account for lifting mechanisms, which largely determine the physical impacts of severe storms and their patterns. This leaves a gap between results and reality, but is ultimately considered by many to be the best approach because of its consistency and lower bias. This study adds to the literature by using 20CR to look at these parameters on a much longer time scale. Many results had parallels to previous research, but poses new questions as a recently developed dataset over a long temporal scale.

Compared to previous results, 20CRv3 displays similar trends in frequencies of NDSEV both spatially and seasonally. The increase of severe weather frequency in the Southeast United States and in the early spring is supportive of what has been shown using various approaches, and consistency throughout the 180-year time period promotes promising results. This allowed us to believe that 20CRv3 reasonably emulates severe storm environments on a large scale. Understanding the physical forcing behind these patterns will require more research, but more work with a longer time scale such as this one should provide sufficient sample sizes for vast potential to move forward in this area.

Like many weather and climate models, limitations become evident in displaying magnitudes. Sharp inconsistencies existed temporally and reveal the challenges of assimilating data from various sources into one model. Models like 20CRv3 that provide an instantaneous screenshot of the atmosphere can also lead to less smooth results when looking at averaged and blended trends. Magnitude outputs are also from much more specific results and parameterizations. All in all, these results make it difficult to come to conclusions about how intensity of storms have changed over time. While the magnitudes of variables such as CAPE produced questionable and inconsistent results, the number of days of CAPE reaching a certain threshold was much smoother and more reasonable.

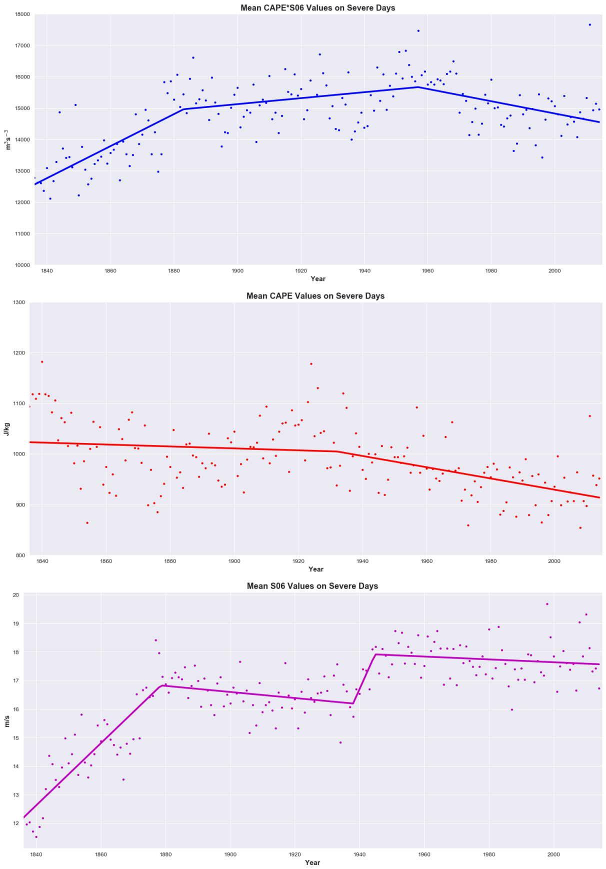

FIG. 8. Mean (top) CAPES06 , (middle) CAPE , and (bottom) S06 values given CAPESO6≥10,000 by year. Piecewise linear regressions were utilized to identify breakpoints.

It appears that 20CRv3 may do relatively well with large scale and broad data, but has shortfalls with more detailed output. In other words, reanalysis so far may be able to accurately say that severe weather is happening, but less about the storms themselves.

5. Conclusions and Future Work

NDSEV has shown weak trends as a whole in the United States from 1836–2015. This suggests that the frequency of severe storm days nationally has shown little changes on average. However, patterns lie between spatial and seasonal scales in ways that are not new to severe storm climatology research. This study supports these trends by showing their occurrence over a longer time scale. Specifically, these results signify that

1. NDSEV, NDSEVsig, and days of STP≥1 increases in the Southeast United States and decreases in the Northern Plains

2. NDSEV, NDSEVsig, and days of STP≥1 increases in the spring and decreases in the summer

This study reveals a pattern of these changes occurring consistently over the 180-year time period, suggesting that the 19th century had a majority of its severe storm environment days in the Northern Plains in the mid-to-late summer. One speculation is that warm and unstable conditions of severe weather are increasing in frequency with climate change, creating wider spatial and annual ranges of environments suitable for severe weather.

While it appears that large-scale patterns are detected relatively well, specifics such as magnitudes of severe storm environment parameters provide more uncertainty. Future research could also help to verify aspects and time periods of 20CRv3 depicted most and least accurately. More work is necessary to understand how much of these results are truthful snapshots of historical environments, and how much is due to issues of observations assimilated into the reanalysis. Overall, evaluating severe weather climatology through reanalysis allows researchers to access more data and avoid significant biases of the storm-reporting database.

Similar methods on a time scale this long could prove to be extremely useful in understanding severe weather climatology and climate variability in the future, with both natural and anthropogenic relations. Possibilities of future work exist in examining the extent to which spatial and annual changes are happening and the physical mechanisms behind them, if any. Additionally, examining convective precipitation could be from 20CRv3 could help to create climatologies closer to reality and reconstruct historical storms that actually occurred. This study supports previous results on a temporal scale and aids in providing questions to be answered about storm climatology and reanalysis techniques.

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